A Precision Hybrid Inertial/Acoustic Navigation System for a Long-Range Autonomous Underwater Vehicle

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ABSTRACT

The Canadian Department of National Defence has developed an autonomous underwater vehicle (AUV) capable of performing long-range missions in ice-covered waters. Autonomous operations in such an extreme environment, often where *a prioi* knowledge of the bathymetry is limited, requires a navigation system that is precise, reliable and repeatable. A hybrid navigation system has been developed which provides precise navigation by combining data from two different types of sensors: inertial and acoustic. This navigation system has been integrated into a large AUV, and for mission lengths of up to 200 km it has *demonstrated* horizontal navigational accuracies of better than 0.05% of distance travelled.

This paper describes the AUV and its mission, followed by details on the specific navigation sensors selected and how the overall navigation solution is mechanized. It then describes the behaviour of the navigation system during field experiments and during a successful long-range under-ice mission in the High Arctic.

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INTRODUCTION

The Canadian Department of National Defence, in collaboration with International Submarine Engineering Research (ISER), of Vancouver, B.C., has developed an Autonomous Underwater Vehicle (AUV) capable of performing long-range missions in the ice-covered waters of the High Arctic [1], [2]. Design started in 1992, and construction was complete by 1995. The vehicle was used in the spring of 1996 to lay 180 km of fiber-optic cable from a shore site to a site in the Arctic Ocean, where the cable was spliced to a bottom-mounted experimental system. The vehicle then returned to the shore site where it was recovered. Although the vehicle was used in this mission to lay cable, there is no reason why it could not perform other tasks.

The main purpose of this paper is to describe the navigation of the vehicle, but it begins with a more general discription of the vehicle and the mission for which it was designed.

[1] Currently employed by MacDonald Dettwiler, Richmond, British Columbia, Canada.

THE MISSION

A typical under-ice cable-laying mission has the following general operational requirements:

- Launch from an ice camp through ice that is several metres thick.
- Transit up to 200 km over relatively unknown ocean-bottom terrain while dispensing a fiber optic cable
- Maintain a relatively constant altitude above the seafloor
- Avoid bottom obstacles and surface ice keels
- Deliver the cable to a remote ice camp (in this case by 'flying' through a loop of rope suspended below the ice)
- Return to the launch hole for recovery

THE VEHICLE

The vehicle was named *Theseus* after a hero in Greek mythology. It was he who braved the labyrinth on the island of Crete in order to slay the Minotaur. As he worked his way to the centre of the maze he laid down a golden thread given to him by the king's daughter Ariadne. After slaying the Minotaur, Theseus followed the thread out of the maze back to safety. The loose parallel between the present-day cable laying mission and a tale from Greek mythology makes the choice of name plausible.

Theseus (the AUV) consists of a segmented aluminum pressure hull with free-flooding fiberglass hull sections fore and aft of the pressure hull. The pressure hull is segmented into six sections, primarily for ease of air transportation. A general arrangement of the vehicle is shown in Figure 1. Figure 2 shows Theseus being lowered into its ice hole prior to start of an under-ice mission The key design parameters for Theseus are listed in Table 1.

Table 1 - Theseus Key Design Parameters

Design Parameter	Value
Length-Over-All	11 metres (36 feet)
Diameter	1.27 metres (50 inches)
Working Depth	1000 metres (3280 feet)
Displacement	8,845 kg (19,500 lbs)
Range	> 400 km (215 nm)
Speed (nominal)	2.0 m/s (4.0 knots)

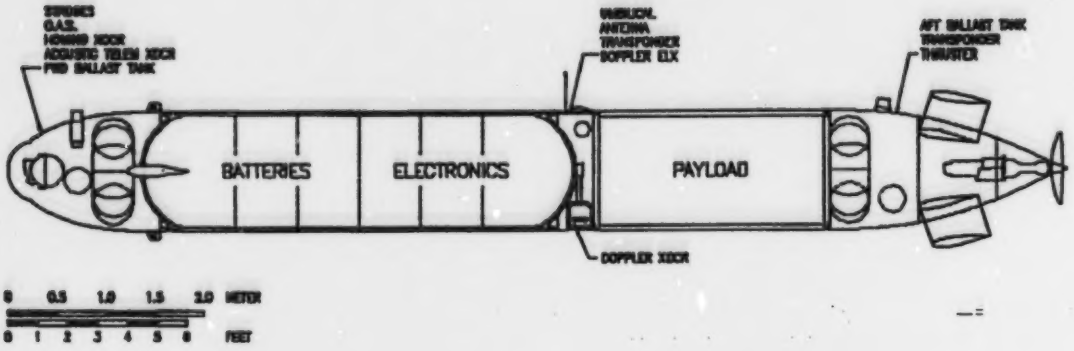

Fig. 1 - Theseus General Arrangement (side view)

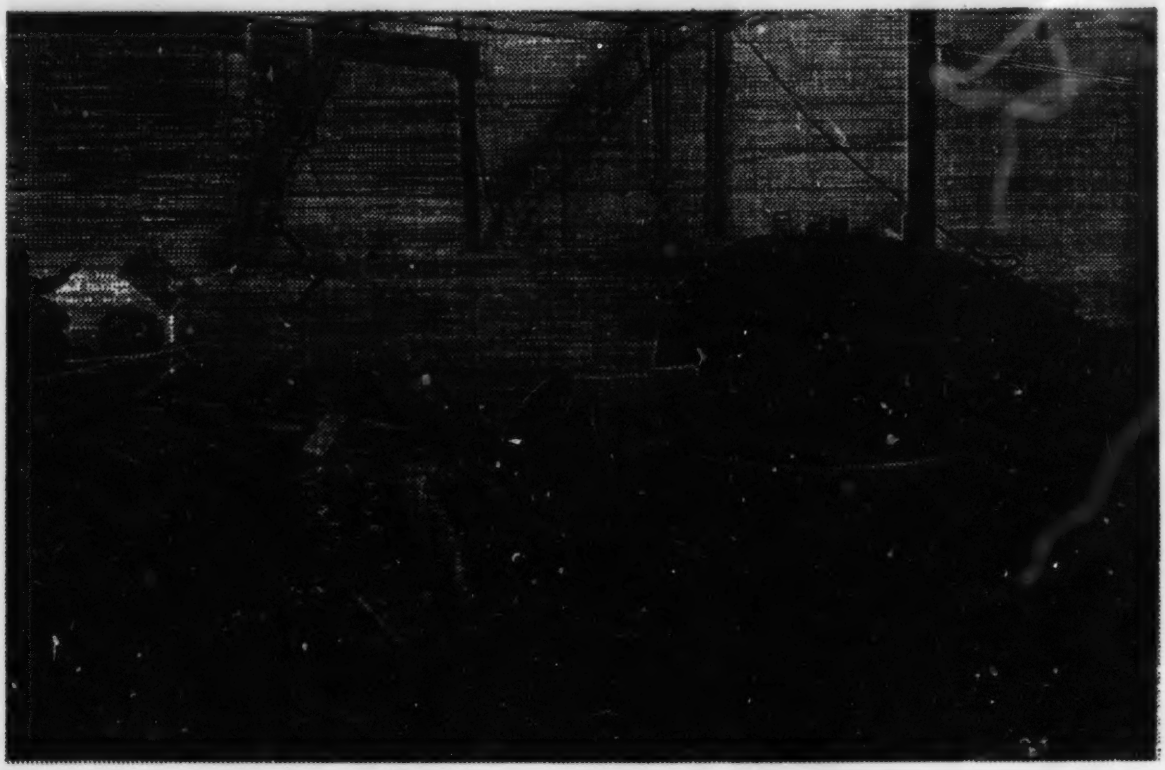

Fig. 2 - Theseus Launched Through Ice Hole

The free-flooding nose contains a forward-looking obstacle avoidance sonar, a variable ballast tank, and transducers for acoustic telemetry and acoustic homing. The pressure hull houses several banks of silver-zinc batteries, electrical power distribution, an onboard computer, an inertial navigation unit, and most of the 'dry' electronics. The free-flooding sensor section immediately aft of the pressure hull houses a doppler sonar, a medium-frequency tracking transponder and a radio telemetry antenna (used during open water trials). The free-flooding payload section houses the fiber-optic cable packs and buoyancy compensation tanks. The free-flooding tail section houses a second variable ballast tank, a low-frequency emergency transponder, thruster motor and gearbox.

Six independently moveable hydroplanes, two at the bow and four at the stern, are used to provide vehicle stability and control in pitch, roll, yaw and depth. The foreplanes are used collectively to control depth and pitch, and are used differentially to control roll. The aftplanes are used collectively to control depth, pitch and yaw, and differentially to control roll.

For the Arctic mission eleven fiber optic cable packs were spliced together prior to installation. Each pack contained 20 km of 2-mm-diameter fiber-optic cable, thus providing a single fiber-optic cable 220 km in length. The cable was wound concentrically in the packs and was held together with a special glue with a tear strength of less than 2 lbs. As the vehicle moved forward, tension on the cable exceeded the glue strength, and the cable was dispensed out of a tube extending aft past the propeller. Since the fiber is heavier than seawater (i.e., a specific gravity greater than 1.0), the vehicle became more buoyant as cable was dispensed. The onboard computer allowed seawater to fill the buoyancy compensation tanks surrounding each pack as fiber was dispensed.

Part way through the vehicle development program, it became technically feasible for the AUV to utilize the fiber-optic cable it was laying as a telemetry link during the outbound phase of the mission. This was found extremely useful.

NAVIGATION SENSORS

Introduction

Navigating underwater in any type of vehicle can be difficult. Theseus' requirements were particularly challenging:

- The vehicle must travel up to 200 km to within ±50m of a specific position, then return home
- The vehicle must operate in waters with 100% ice coverage
- The vehicle must operate at high latitudes (>80°N)
- The vehicle is to be unmanned (i.e., computer-controlled)
- The vehicle is to be autonomous (i.e., must operate without human assistance)
- The vehicle must have very high reliability

Performing long-range, multi-day missions requires an accurate navigation system. Operating under a permanent ice cover imposes additional constraints. All navigation sensors must be located under the ice cover, but not necessarily onboard the vehicle. A hybrid solution to this problem was chosen:

- A medium-accuracy, velocity-aided inertial navigator which provides dead-reckoned position estimation for en-route navigation, and
- An acoustic homing system used for terminal navigation and to provide position updates (fixes) at specific points along the mission route.

This paper will deal primarily with the two dimensional (horizontal) navigation problem. The location of the vehicle in the vertical is measured two ways: a pressure transducer measures vehicle depth below sea level, and a sonar measures height above the seafloor (altitude).

The navigation sensors selected for Theseus are summarized in Table 2.

Table 2 - Theseus Navigation Sensors

Sensor	Manufacturer/Model	Provides	Accuracy
Inertial Navigation Unit	Honeywell MAPS	Heading (true)	0.1°
		Position (lat/long)	0.8 nm/hr[note 1]
		Velocity (free inertial)	2.5 ft/s[note 2]
		Attitude	0.05°
Doppler Sonar	EDO 3050 DVL	Forward/lateral ground speed	0.2%[note 3]
		Forward/lateral water speed	0.5%
		Altitude (above seafloor)	0.3 m
Acoustic Homing	Datasonics ACU-206	Range to transponder	1-2 m[note 4]
		Bearing to transponder	±5°
Pressure Transducer	Paroscientific 8B1400	Depth (below sea level)	< 2 cm

Notes: 1) Circular Error Probable, for flights less than or equal to 1.0 hr
2) For flights up to 2 hrs
3) Percentage of forward velocity
4) Not including errors due to acoustic ray bending

Inertial Navigator

The Honeywell MAPS INU is a medium-accuracy strapdown inertial navigation unit [3] that provides a full set of navigation sensor data to the onboard computer via a MIL-STD-1553 bus. In theory, the INU alone could be used to provide the complete navigation solution for an under-ice AUV mission, since it requires no external sensors. In a practical application however, additional sensors are required due to certain inherent weaknesses of the INU.

The inertial velocities reported by the INU are subject to *Schuler oscillations*, a characteristic of Schuler-tuned inertial platforms [4], [5]. When disturbed by short-term errors such as accelerometer bias or scale factor, the INU's inertial velocity measurements will oscillate like a Schuler pendulum. Figure 3 shows the free-inertial velocity V_X of an aligned Honeywell MAPS INU over the period of several days. Following a two-hour gyrocompass alignment, the Schuler oscillations, with a period of approximately 84 minutes, dominate the display. Since these unbounded oscillations are a significant percentage of the AUV's normal operating speed of 2 m/s, they will seriously degrade any position estimations.

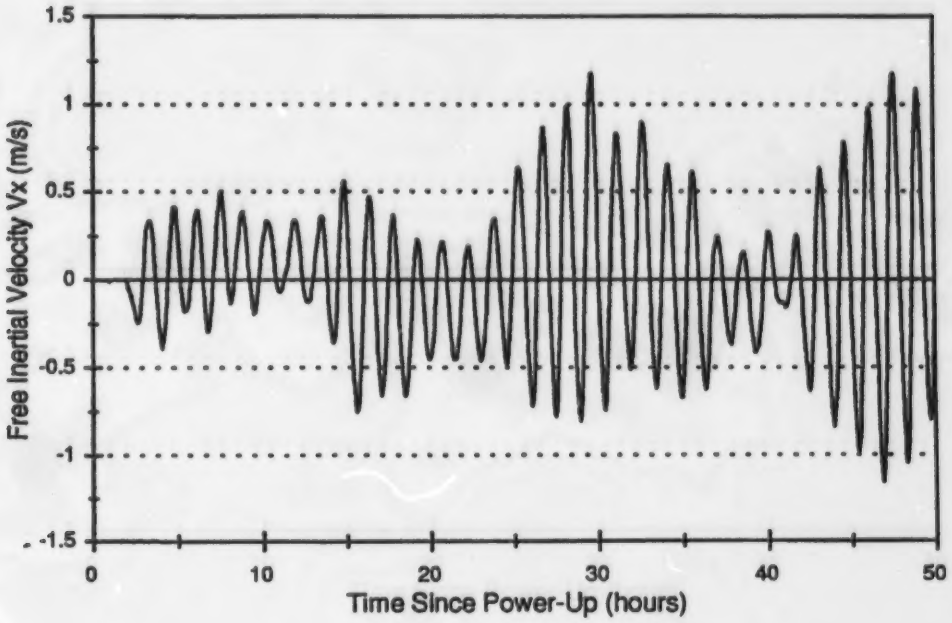

Fig. 3 - Schuler Oscillations of an Aligned Honeywell MAPS INU
82°30'N 62°12'W, April 17-19, 1993

To mitigate the growth of the Schuler oscillations and to bound the position estimation error, the INU is operated in *velocity-aided* mode. In this mode, the INU is continually provided with velocity corrections by the onboard computer. These corrections are simply the difference (taking reference frames into account) between the inertial velocities reported by the INU and those reported by other sensors which have better long-term, bounded error characteristics. The ultimate effect is that the INU uses the velocities that are provided by the better sensors.

Doppler Sonar

The EDO 3050 doppler sonar provides forward and lateral ground-referenced velocities when the doppler is within acoustic range of the seafloor (typically 150-200 m at a frequency of 287.5 kHz). The velocity measurements are very accurate, stable and are bounded in the long-term. They are obtained by a phased-array transducer which generates four downward-looking acoustic beams that are perpendicular in azimuth (fore, aft, port, stbd) and oriented 60° down from the horizontal plane. The doppler shifts from returns off the seafloor are averaged to provide highly accurate forward and lateral speed measurements. Measurement of two-way travel time of each beam provides an average measurement of the vertical distance to the seafloor (altitude). This configuration of four beams is referred to as the 'Janus' configuration since it looks both forward and backward, as does the Roman god that it was named after. This particular configuration minimizes the effects of transducer pitch and roll. Simultaneous water-referenced velocities are also available when there is at least 30 metres of water below the doppler transducer face. When sonar returns from the seafloor are too weak due to excessive altitude or poor reflectivity, water-referenced velocities can be used for navigation. However, these will not be as accurate as ground-referenced velocities, especially when water currents are present.

Mechanical alignment of the doppler transducer and the INU must be very precise, repeatable and immune to environmental disturbances. Figure 4 shows the mechanical assembly used to mount these two sensors. The INU is bolted to an aluminum mounting plate situated at the center of the end dome on the aft end of the pressure hull. A precision, water-tight through-hull fitting connects the INU mount with the doppler transducer mount. This location (the center of the end dome) was chosen because it is the location that suffers minimal hull deformations due to water temperature and pressure.

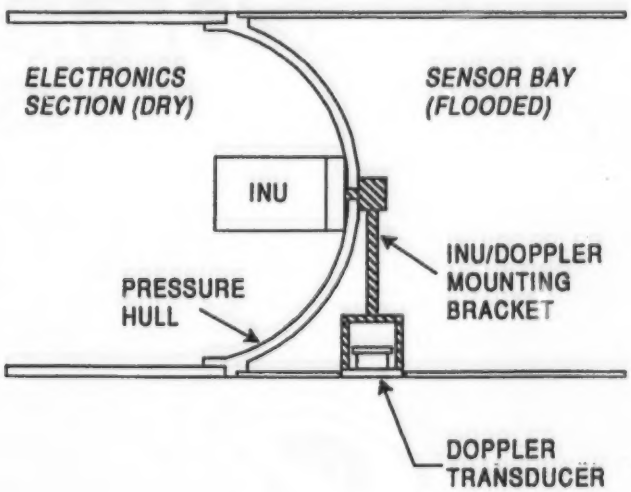

Fig. 4 - INU/Doppler Precision Mount

Acoustic Homing

After dead reckoning for several hundred kilometres at low speeds, even a velocity-aided inertial navigator can build up significant position errors. To ensure that the AUV could reach its destination and deliver the fiber-optic cable, a low-frequency acoustic homing system was used periodically to update the internal navigation and for terminal navigation at the cable delivery site.

The Datasonics ACU-206 Homing System measures range and relative bearing to an acoustic transponder. This system consists of an electronics box located inside the pressure hull and an acoustic transducer located in the (flooded) nose of the AUV. For the under-ice mission, acoustic transponders were deployed at key locations by lowering them on ropes through holes drilled into the ice. Each transponder had specific interrogate and reply frequencies, which, of course, were different from each other. Several different frequencies in the 8-12 kHz range were used during the cable-laying mission.

At pre-planned points in a typical mission, the onboard computer powered up the homing system, which sent out acoustic pulses at the interrogating frequency of the expected transponder. Once a response was obtained, the range was computed from the combined travel time of the transmit and reply signals and the assumed speed of sound through the water. The bearing to the transponder, relative to the vehicle's heading, was obtained from the transponder's reply signal, the necessary phase information being measured by an array of receive elements in the transducer. The measured bearing provided enough information for the guidance subsystem to steer the AUV towards the transponder. Also, the combination of range, bearing and the known geographic position of the transponder allowed the AUV to update its own position.

Arctic field trials [6] with this and similar homing systems have demonstrated that they are capable of acquiring a transponder at ranges in excess of 5 km under good acoustic conditions.

NAVIGATION MECHANIZATION

Reference Frames

Development of any navigator begins with a definition of the reference frames to be used. In this navigation system, four standard reference frames are of interest:

Chassis: Also known as the Platform frame. A right-handed, orthonormal coordinate system defined by the input axes of the the inertial sensors. The coordinate axes and origin are fixed to the INU's physical chassis by the manufacturer's mechanical design.

Body: Also known as the Vehicle Body frame [7]. A right-handed, orthonormal coordinate system with its origin fixed to the vehicle center of mass. Coordinate axes are fixed to the vehicle, and are defined by the pitch, roll and yaw axes of the vehicle.

Nav: A locally level (perpendicular to the reference ellipsoid) wander angle frame [7]. Origin is at the location of the inertial navigation system.

ECEF: Short for Earth-Centered-Earth-Fixed. A right-handed, orthonormal coordinate system with its origin at the mass center of the earth [7]. Axes are located along the polar axis, the prime meridian, and 90° W longitude. Geographic position is denoted in terms of geodetic latitude and longitude.

The INU measures its orientation in its own 'Chassis' frame of reference. This must be transformed to the 'Body' frame of reference to provide the orientation of the vehicle. These two frames of reference, although fixed to each other, do not necessarily line up with each other. The introduction of two separate frames gives greater flexibility to the user. The two frames are tied together by way of the *orientation* and *boresight* angles, which are input to the INU at initialization. Orientation angles for pitch, roll and yaw are multiples of 90°. Boresight angles allow for 'fine tuning' of the INU orientation about the pitch, roll and yaw axes to within ±45°. These angles were accurately measured following construction of the INU mounting assembly.

Sensor data is transformed from the Body frame of reference to the Nav frame using a direction cosine matrix called C_{BN}, which is generated internally by the INU and transmitted on its MIL-STD-1553 interface. The INU inertial velocities, which are discussed in the following section, are output in the Nav frame.

Finally, the INU transforms the vehicle position from the Nav frame to the ECEF frame, in latitude and longitude.

Velocity-Aiding

A block diagram of the dead reckoning segment of the Theseus navigation system is shown in Figure 5. The INU performs all navigation calculations, and it provides position and attitude to the onboard control computer.

Velocity corrections, in the Nav frame, are transmitted to the INU by external software at a rate of five times per second, based on external velocity sensor data. This sensor data is transformed from the Body frame to the Nav frame using the C_{BN} matrix. The velocity corrections are simply the difference between the inertial velocities reported by the INU and those provided by the external velocity sensor. The 'best available' velocity sensor data is selected using the following priorities (first being the highest):

- Ground-referenced doppler velocities (forward/lateral)
- Water-referenced doppler velocities (forward/lateral)
- Vehicle speed-thru-water estimate (forward)

The doppler sonar is provided with real-time vehicle pitch and roll at 2 Hz to correct velocity readings at non-zero pitch and roll angles. An 'INU Yaw Correction' input provides the capability to remove any misalignment in yaw between the INU heading and the doppler transducers. This is accomplished in the doppler firmware, which in effect rotates its velocity readings by the specified angle. Also, when the vehicle is 'parked' on the seabed or up against the ice the velocity readings transmitted to the INU are arbitrarily set to zero in order to ensure that erroneous values are not used.

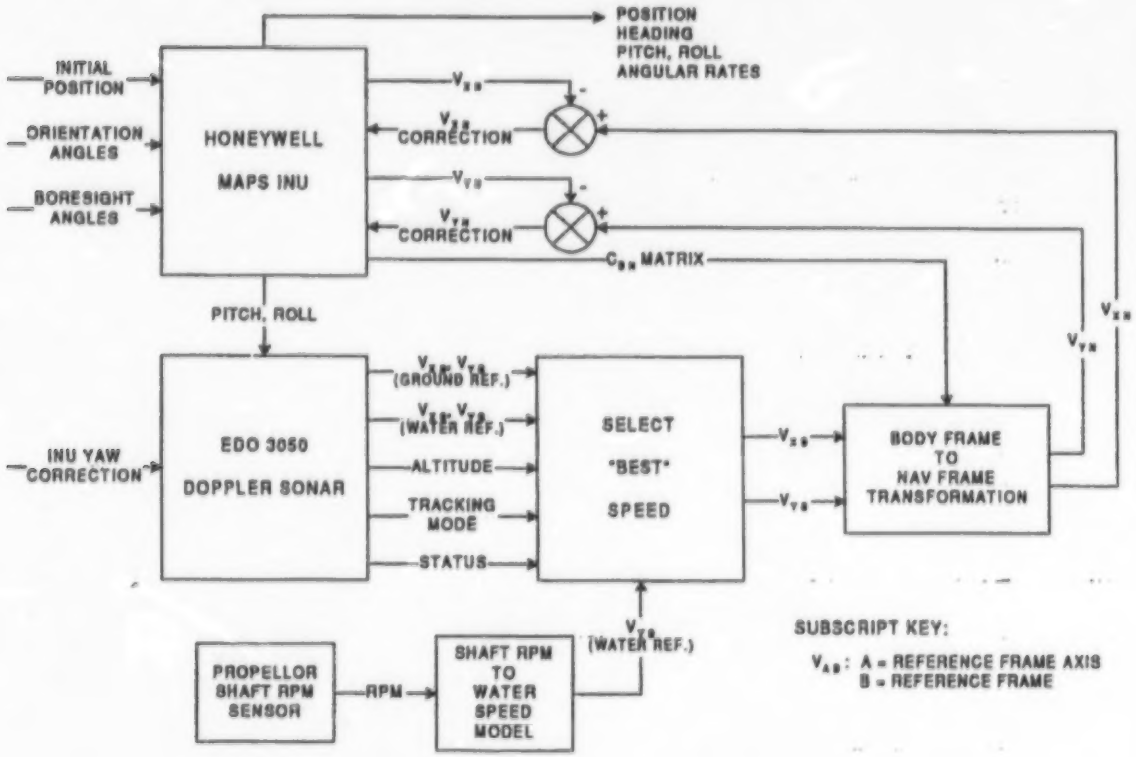

Fig. 5 - Theseus Dead Reckoning Navigation System Block Diagram

Position Updates

As stated earlier, the vehicle can autonomously update its position with its acoustic homing system if it has a valid range and bearing to a transponder that has a known position. As well, an operator can input a position update if a telemetry link with the vehicle is available.

An optimal position reset would combine the position error (difference between the position update and the position reported by the INU) with data from the INU, and provide position, velocity, attitude, gyro and accelerometer corrections in a coherent manner. This would normally be done with a Kalman filter. However, there were no funds and no time to develop such a filter.

A more straightforward approach was taken to permit 'crude' position updates, as shown in Fig. 6. At the instant that a position fix is obtained, latitude and longitude offsets are computed based on the difference between the position fix and the position reported by the INU . These offsets are then added to all subsequent latitude and longitudes reported by the INU. The offsets are stored in non-volatile memory in the onboard computer, to ensure that they are available should the computer experience a cold or warm re-boot during a mission.

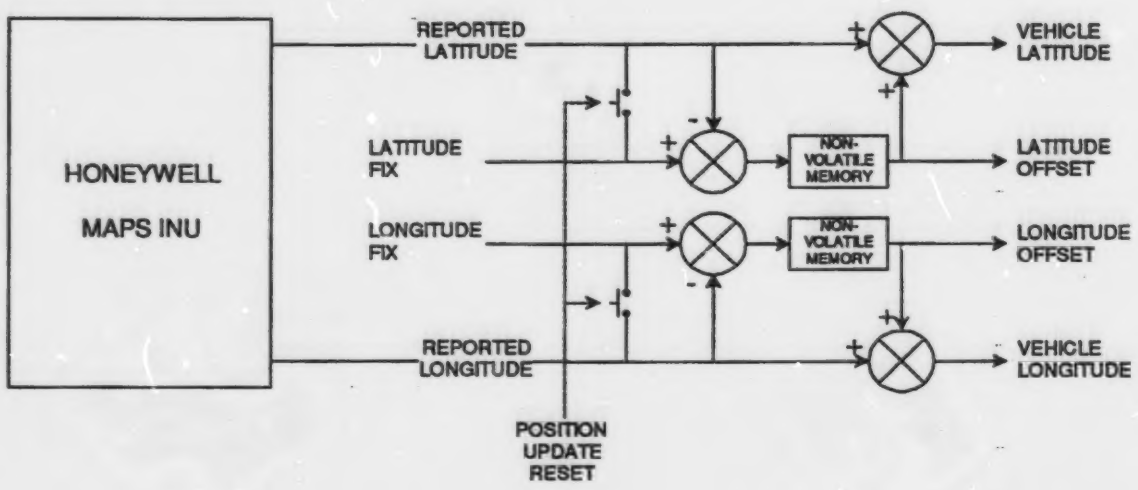

Fig. 6 - Theseus Position Updates

AUTONOMOUS GUIDANCE CAPABILITIES

Three different guidance controllers are available for autonomous navigation: *targeting*, *line following* and *homing*. Each of these 2-D controllers generates heading setpoints to the vehicle's autopilot, and are described briefly below.

Targeting

The *targeting* controller steers the vehicle directly towards a waypoint, which is a geographic position. Each time the INU reports a new position (typically once per second), the targeting controller computes the heading from the current vehicle position to the waypoint. Since this controller is fairly simple, the vehicle may make its 'final' approach to the waypoint from an unpredictable heading when it is used in the presence of cross-currents. Because of this possible behaviour, this controller is used only under specific conditions.

Line Following

When it is necessary for the vehicle to follow a straight-line trajectory between two waypoints, the *line following* controller is used. Each time the INU reports a new position, the controller adjusts the vehicle's heading so as to decrease the cross-track error. This is done using a simple proportional-integral-differential (PID) controller. Extensive sea trials have demonstrated that Theseus can consistently stay within two or three metres of a line.

Homing

Homing is an acoustic version of *targeting*. Each time the homing system measures a range and relative bearing to the transponder being interrogated, the homing controller adjusts the vehicle's heading so as to keep the relative bearing at 0° (directly ahead). A contingency mode of homing is provided for the unlikely situation where the INU has failed, and the heading autopilot is unable to operate. In this situation, the homing controller directly controls the vehicle's aftplanes to yaw the vehicle towards the transponder.

Homing was used during terminal navigation to deliver the fiber-optic cable to the remote ice camp, as shown in Figure 7. Two transponders were deployed from the surface 1.2 km apart in such a way that they lined up with the center of the cable recovery loop. When the AUV arrived in the vicinity, it began to interrogate the first transponder. When it replied, the AUV steered towards it. Once homing to the first transponder was completed, the vehicle began homing to the second transponder. The effect of this double homing was to force the vehicle to fly through the cable-recovery loop along a prescribed path.

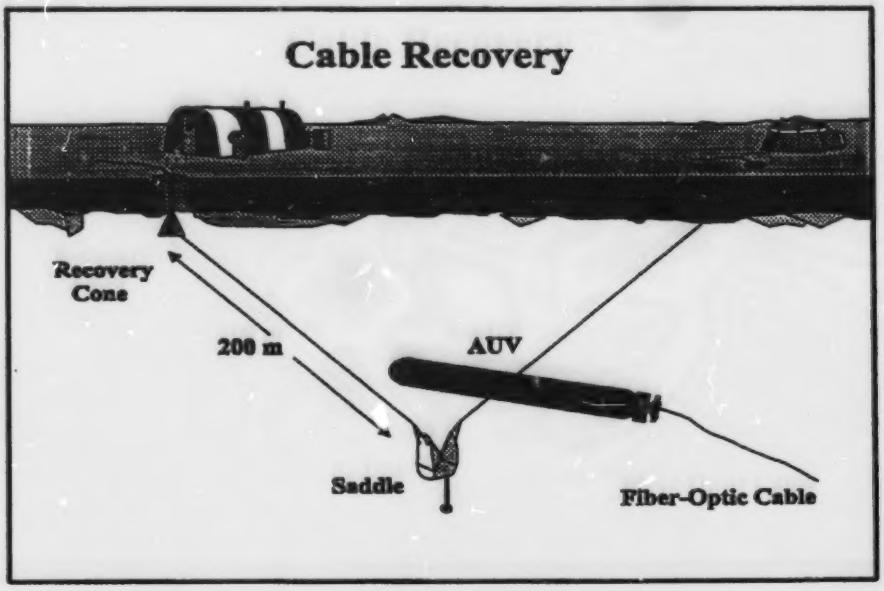

Fig. 7 - Under-Ice Fiber Optic Cable Delivery

NAVIGATION ERROR MODEL

Theseus was required to navigate long distances by dead-reckoning alone, with an occasional position update from the acoustic homing system. In order to know where to place the transponders, it was necessary to be able to estimate the vehicles's dead-reckoned position error. In particular, it was necessary for the position error at the transponder site to be significantly smaller than the operational range of the homing system; this would ensure acoustic 'capture' at the transponder. A navigation error model was developed to help make these estimations.

An error model for a navigation system is usually based on the derivatives of the mechanizations of the navigation equations. Such a derivation is difficult if the mechanizations and details on the inertial sensors are not available, as was the case for Theseus. Since dead reckoning navigation consists of integrating heading and speed over time from a known starting position, a basic error model was chosen consisting of error terms for these values:

ε_P	Initial position error
ϕ_0	Initial heading error
ϕ_{DI}	Doppler/INU heading misalignment
δV_0	Doppler cross-track velocity error

The vehicle's estimated error was taken to be the root-sum-squared (RSS) of the measured 1-σ values for the above errors. This error model concentrated on cross-track errors, as opposed to along-track errors. This was decided since the vehicle's mission was to come close enough to a transponder to acquire it - a substantial along-track error would not prevent such an acquisition. In using this model, the following assumptions were made:

- Each error source is independant of the others (i.e., errors are uncorrelated)
- Each error term has a Gaussian distribution with zero mean and an estimated standard deviation.

The estimates of the standard deviations are given in Table 3. Each of these errors is discussed in more detail below.

ε_P: The positions of two corners of the launch tent were determined by surveying them with a Geodimeter from a survey point on a hill overlooking the ice-covered bay. The position of this survey point had been measured with P-code GPS, and the orientation of the Geodimeter was determined by a series of sun sights. The position of the vehicle inside the tent was interpolated from the two surveyed corners. The overall error in the vehicle's initial position was approximately 10 metres.

ϕ_0: This error is the difference between the heading reported by the INU immediately after gyrocompass alignment and its true heading. Extensive field trials performed by the authors in the High Arctic [6] in 1992 and 1993 verified that the Honeywell MAPS INU could repeatably align itself to within 0.1° (1σ) of its true heading.

This error term has a constant value immediately following INU gyrocompass alignment, and its contribution to vehicle position error is simply $D*\sin(\phi_0)$, where D is the straight-line distance from the starting point to the 'present' point of the vehicle.

ϕ_{DI}: As shown in Figure 5, a strap-down situation is assumed (i.e., the INU and doppler are both in the Body frame of reference). Any misalignment in heading between the INU and doppler transducer results in an error (ϕ_{DI}) similar in nature to that caused by ϕ_0.

δ_{V0}: This is the broadside or lateral error of the doppler sonar. The manufacturer quotes it as a percentage of the forward velocity.

Table 3 - Navigation Position Error Estimates

Error Term	Value	Contribution	Value (m)
ε_P	10 m	ε_P	10
ϕ_0	0.1°	$D * \sin(\phi_0)$	366.5
ϕ_{DI}	0.1°	$D * \sin(\phi_{DI})$	366.5
δV_0	0.2%	$D * \delta V_0$	420
		Total error (1σ):	667
		(3.3σ):	2,202

where: D = estimated mission length (210 km)

The 3.3σ quoted above is the range inside which the vehicle will be found with a 99.9% probability. A dead-reckoned position error of approximately 2,200 metres is significantly less than the measured range of the acoustic homing system (5,000 metres). This provides a healthy safety margin for transponder acquisition.

In spite of the predictions in Table 3, three transponders were deployed along the mission route for position fixes, in order to increase the likelihood of mission success.

FIELD EXPERIMENTS

The unique environment of the Arctic Ocean can have a significant effect on inertial and acoustic navigation sensors. Specifically, high latitudes affect the ability of any inertial navigation system (INS) to gyrocompass align. Under-ice acoustic conditions affect the performance of nearly all acoustic devices. The potential effects of these conditions on vehicle navigation, and hence mission success, were recognized early in the project. A number of field experiments were undertaken from 1992 through 1995 to address these concerns and to quantify navigation sensor performance under the conditions expected during the cable-laying mission.

INU Heading Alignment

A very accurate initial heading was required to ensure accurate navigation for the cable-laying mission. It was hoped that the self-alignment capability, or *gyrocompassing*, of the Honeywell INU would be sufficient to provide an initial heading error of 0.1° or better.

During gyrocompassing, the INU determines its initial heading by measuring the horizontal component of the earth rate. As this component is quite small above 60-65° latitude, most INS's have difficulty in gyrocompassing at high latitudes. Although the INU was qualified for navigation at any latitude, its gyrocompass alignment performance above 65° latitude was known only theoretically. Since the launch site for the cable-laying mission was above 82°N latitude, it was decided that field experiments were necessary to quantify the INU's alignment performance.

More than 100 separate INU alignments were made at CFS Alert (82° 30' N) in 1992 and 1993 [6], varying a number of key parameters: length of gyrocompass alignment time, the initial heading, and yaw motion during alignment. The following alignment procedure was repeatedly found to provide an initial heading error (ϕ_0) of less than 0.1°:

- Orient the INU at a non-cardinal heading (a heading other than 0°, 45°, 90°, 135°, ...)
- Power up the INU and download initial position
- Switch INU to gyrocompass alignment mode
- Leave INU undisturbed for 30 minutes
- Rotate the INU clock-wise 90° over a 15 second period
- Leave INU undisturbed for 90 minutes
- Switch to air-align mode (navigation mode)

It is not clear whether the 90° rotation improves alignment performance by improving system observables [8], or because it compensates for ring laser gyro 'lock-in' [9]. Given that the Honeywell INU employs mechanical dithering to overcome lock-in, it is likely that this is not the cause. However, it is beyond the scope of this paper to investigate this further.

This 'two-position, non-cardinal alignment' procedure could easily be performed as part of the mission pre-dive sequence. As stated earlier, the INU is bolted to a special mounting bracket inside the pressure hull to ensure accurate alignment with the doppler sonar transducer. To accomodate the above alignment procedure, a removable shelf was designed for this bracket. The INU sits on the shelf during the alignment procedure, and once the 2-hour alignment is completed, the INU is in a position to be bolted to the bracket with a minimum of extra motion.

Acoustic Homing

The Arctic Ocean has several unique characteristics that affect acoustic propagation: extremely low water temperatures (-1.5° C), a permanent ice cover and relatively unknown bottom terrain (bathymetry). Because of the uncertain propagation, a substantial amount of experimentation was

performed in order to ensure that the acoustic homing system used in Theseus would operate as required.

Variations in the speed of sound, both vertically and horizontally, have a significant effect on how sound propagates underwater. From 1992 through 1995, dozens of sound speed measurements were taken in the Lincoln Sea north of Ellesmere Island, using devices called Conductivity-Temperature-Depth (CTD) profilers. A CTD 'cast' is made by drilling a hole in the ice at the required location, lowering the CTD to the seafloor on a line, then retrieving it. The CTD records the conductivity, temperature and depth during its downward and upward journeys. This data is then used to compute the speed of sound at each depth, providing a vertical sound speed profile for that particular location. Each cast also provides an accurate measurement of water depth as well, assuming that the CTD reaches the seafloor.

Knowledge of the sound speed profile, ice cover thickness and sea bottom bathymetry provided sufficient data to model the acoustic propagation at locations along the mission route. A standard acoustic modelling technique called *ray tracing* [10], was used to estimate the effective transponder range as a function of acoustic source level, frequency and transmitter and receiver depths. This modelling also assisted in determining optimum depths for the transponders and the vehicle.

A number of candidate acoustic homing systems were field-tested *in situ* over the same time period. Various frequencies, power levels, water depths and horizontal ranges were used [6]. Slant ranges of over 5 km were attainable in deeper water, with somewhat shorter ranges in shallower waters. Data collected from these trials assisted in developing the overall mission plan, particularly as it pertained to the locations and depths of the acoustic transponders.

TRIALS RESULTS

Arctic Shakedown Trials

The first Arctic trials were held in April 1995 in Jolliffe Bay, a small bay just 6 km west of Canadian Forces Station (CFS) Alert, in the Northwest Territories (82° 30' N, 62° 42' W). This site was the same as that of the full cable-laying mission the following year. The reason for these shakedown trials was partly one of logistics and field technique. We wished to test the procedure for assembling the vehicle at a remote location and refine our techniques for launching and recovering the vehicle through the solid cover of pack ice. The main reason for the trials, however, was to test the vehicle and all its systems in the under-ice environment.

Four under-ice runs were carried out, the longest of which was 5 km. Since the acoustic telemetry was not yet trusted to give good communications with the vehicle, control was exercised through the fiber-optic cable that was dispensed during the dive.

This was wise, for the acoustic telemetry at first behaved very poorly. However, it was found that the propulsion motor controller was operating at a frequency very close to that of the telemetry and was seriously interfering with it acoustically. When the interference was reduced (by

wrapping the motor with bubble pack) the acoustic telemetry's operable range increased to 3 km, which was a reasonable distance for the shallow waters adjacent to Jolliffe Bay. Following these trials, the motor controller frequency was permanently changed to eliminate this interference problem.

The homing system was tested successfully out to ranges in excess of 7 km when both source and receiver were fixed and out to 3 km when the source was moving.

The vehicle's cable dispensing system worked well, as did the techniques for launching and recovering the vehicle through the two-metre-thick ice.

Navigation Trials at Nanoose Range

The first extensive navigation trial was held at the Canadian Forces Maritime Experimental and Test Range (CFMETR) at the Nanoose Range (Vancouver Island, British Columbia) during January 1996. The trial, which was the length of a full Arctic mission, was held to confirm vehicle endurance and reliability as well as to test the navigational accuracy.

Theseus ran eight circuits around a 20-km-long range plus the distance to and from the range for a total of 360 km. The elapsed time was 50.6 hrs. Theseus performed very well, using less than half of its battery power (145 kW-hours out of 360).

The navigational accuracy was determined by comparing Theseus' true position, as determined acoustically by fixed bottom installations on the Range, with its own internally-calculated dead-reckoned position. On the first traverse of the range the vehicle's cross-track error was 0.45% of the distance traveled, and its along-track error was about 0.5%. This cross-track error corresponds to a heading error of approximately 0.26°. Assuming this error to be solely due to yaw misalignment between the INU and the doppler transducer, an INU yaw correction (see Fig. 5) was sent to the vehicle via acoustic telemetry. After this correction was applied, the navigational accuracy on subsequent legs was of the order 0.05% of the distance traveled, a heading error of 0.03°. This exceptional accuracy was much better than had been expected.

The vehicle's ability to home to a transponder was found to work very well out to a range of 5 km, the maximum range attempted during the trial. When Theseus reached the appropriate distance from the transponder, it updated its position without any measurable error.

The Acoustic Telemetry system performed very well for most of the mission; maximum ranges were typically greater than 2 km. However, 40 hours into the run, acoustic communication with the vehicle was unexpectedly lost for the remainder of the trial. The problem occurred when a momentary loss of communications (due to either noise interference or multipath) occurred while a command was being sent to the vehicle. This resulted in an unrecoverable synchronization error in the onboard communications software. Even with the absence of telemetry, the mission was completed autonomously as per the mission plan.

NAVIGATION DURING CABLE DEPLOYMENT IN THE ARCTIC

Two cable-laying missions were carried out in April 1996. The first one, as shown in Figure 8(a), was to an ice camp called Knossos, a one-way distance of 170 km. The second one was to an ice camp called Minotaur, which was about 33 km from Knossos, and, from the navigation point of view, was a repeat of the first mission.

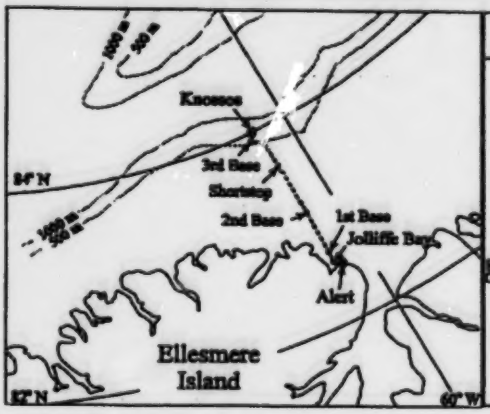

Figure 8(a): Theseus' route in laying the fiber-optic cable from Alert to the ice camp Knossos. The transponder sites are shown.

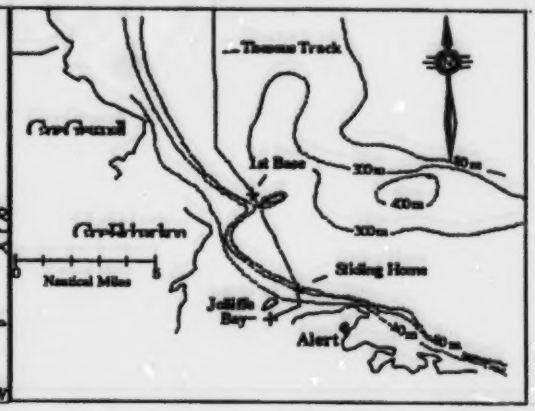

Figure 8(b): The southern portion of the fiber-optic route showing the launching area and the transponder site at 'Sliding Home'.

The cable-laying mission to Knossos consisted of navigating from Jolliffe Bay to Knossos via six sites where transponders had been deployed. Figure 8(a) shows four of these sites: First Base, Second Base, Shortstop and Third Base. Sliding Home, which was quite close to Jolliffe Bay is shown in Figure 8(b). The sixth site, called Catcher, was right at Knossos and just beyond the cable catchment loop. The mission plan called for Theseus to home on each of the transponders in turn to update its position. First Base and Second Base were manned in order to make contact via acoustic telemetry in case the vehicle encountered problems. The transponder at Sliding Home was to aid Theseus in entering a fairly narrow channel on its return trip.

Theseus was launched from Jolliffe Bay at 0022 on 17 April. It passed First Base at 0220 and Second Base at 1112 with successful homing and position updating. At both locations acoustic telemetry was used to contact the vehicle. This was done as a learning experience and as reassurance - not because it was strictly necessary. At Shortstop the homing was not successful because, as was learned subsequently, the transponder was not functioning. Theseus continued on to Third Base, as programmed, where it ascended from a depth of 420 metres to 30 metres and did a successful homing at 0118, 18 April. It then headed toward Catcher, about 1.6 km away. Although the homing to Catcher was good at first, it deteriorated as Theseus approached the catchment loop. Control was taken by the operators back at the control room in Alert, who were still in communication with the vehicle via the fiber-optic cable. They piloted Theseus through the loop using position information obtained from a surface-based acoustic tracking system at

Knossos and relayed to Alert via radio. Theseus successfully flew through the loop and parked up under the ice some 600 m beyond.

After the cable was retrieved from the catchment loop, Theseus' ballast was adjusted for the return trip, via commands over the fiber optic cable. Once this was complete and after a 1-km excess of cable had been pulled up onto the ice, Theseus was commanded to return to the launch site, and the fiber optic cable was cut. The return voyage was truly autonomous.

Theseus returned via Shortstop (where a new transponder had been installed), Second Base, First Base and Sliding Home. The homing step failed to complete at First Base. This was considered to be a major problem by Theseus' navigation fault table since it might mean that there had been a major navigation error. Consequently, Theseus was programmed to stop and park up under the ice where it was to await further instructions via acoustic telemetry. Acoustic contact was established with a unit at First Base, so it was not truly lost. By means of acoustic telemetry it was sent on its way, and at 1140, 19 April, it parked itself under the ice at the launch hole in Jolliffe Bay.

Navigation Accuracy

It is possible to determine Theseus' navigational error at each transponder where it did a positional update. The record of these updates gives the positional accuracy. One must, of course, assume that the position of the transponders was accurate in order to blame the error on Theseus' navigation. There is no doubt of this, however, since the transponders were located with P-code GPS.

When Theseus arrived at Third Base on the outward-bound trip, its cross-track error (as accumulated from Jolliffe) was 0.5% of the distance traveled, and its along-track error was 0.4%.

For the return trip an INU yaw correction was calculated and downloaded to Theseus. Nothing was done for the along-track error since it was not as important. The heading was important so that Theseus would pass close to each transponder (where it was given a corrected position), but an along-track error would not prevent it from passing close to the transponder. With the corrected heading, the cross-track error on the return was 0.04% of the distance traveled, a significant improvement. The along-track error between Short Stop and Second Base was 0.6%, much the same as before. Elsewhere, the along-track records were contaminated and not useable.

Another, more tangible indication of the precise navigation occurred during the second cable laying mission. Due to a failure in one of the vehicle's subsystems near the end of the return transit, it was necessary to deploy an ROV to inspect Theseus on the seafloor. During this inspection, the fiber optic cable laid during the outbound transit was observed in the immediate vicinity of the vehicle. Since the outbound and inbound transits used the same waypoints, it was apparent that the vehicle's return transit was nearly identical to its outbound transit, after having traveled over 250 kilometres.

CONCLUSIONS

A hybrid inertial/acoustic navigation system was developed for the AUV known as Theseus. It enabled Theseus to lay cable with great precision at high latitudes (84° N) and under heavy Arctic pack ice. The navigator has demonstrated an accuracy of approximately 0.05% of the distance travelled and a position drift rate of 4 metres per hour during missions of about 200 km in length and 28 hours in duration. With the acoustic transponder assist to the navigation, Theseus showed itself capable of flying autonomously through a rope triangle (200 metres on side, suspended from the ice) after having travelled 170 km.

During the course of the development of this vehicle, a number of problems related to precise, long-range under-ice navigation at high latitudes were encountered. Through extensive field experiments, these problems were systematically addressed and resolved, expanding the knowledge base in this area, and resulting in a successful cable-laying mission.

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